The Argonne QCD effort

Frank Petriello

DOE Theory Review
July 26, 2011

Motivations for QCD studies

- Existing perturbative QCD formalism only provides a rough guide to obtaining results beyond leading order
- Each step beyond the simplest approximation has required new insights into the structure of QFT (KLN theorem, unitarity methods)
- Still confused about basic conceptual issues: for example, how to define a divergence-free, gauge-invariant kt-dependent parton distribution function?

$$P_i(x, \boldsymbol{k}_T) = \int \frac{dy^- \, d^2\boldsymbol{y}_T}{16\pi^3} e^{-ixp^+y^- + i\boldsymbol{k}_T\cdot\boldsymbol{y}_T} \langle p| \bar{\psi}_i(0, y^-, \boldsymbol{y}_T)\gamma^+\psi_i(0)\,|p\rangle. \quad \boxed{??}$$

from J. Collins, 2003

- Need predictions for LHC backgrounds!

ANL group strengths

- We think about basically all open issues in pQCD:
- Studies of the structure of pQCD at higher orders, and novel methods to obtain NNLO cross sections
- Investigations of fundamental issues such as factorization and resummation using a variety of approaches
- Phenomenological applications of multi-loop QFT, from LHC to g-2
- We turn these studies into predictions and simulation codes heavily used in Tevatron and LHC analyses
- When experimentalists need numbers, they come to us

  - ☑ EW gauge bosons: FEWZ Petriello
  - ☑ Higgs: LHC Higgs working group
    Boughezal, Petriello (convenor & chapter author)
  - ☑ Quarkonium: Quarkonium working group Bodwin (convenor & chapter author)
  - ☑ Double parton scattering: Berger

QCD Phenomenology at the Tevatron and the LHC

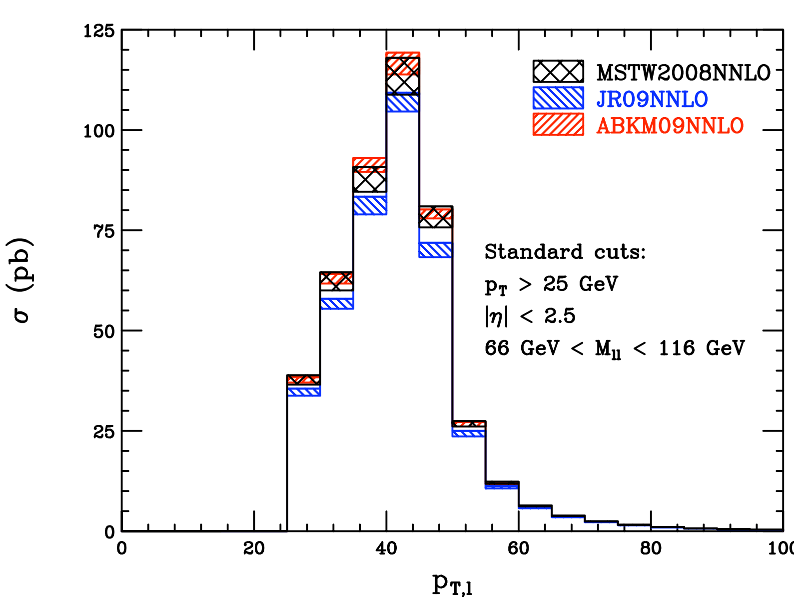
(will be presenting representative examples of group work on various topics; for a more comprehensive listing, see submitted material and backup slides)

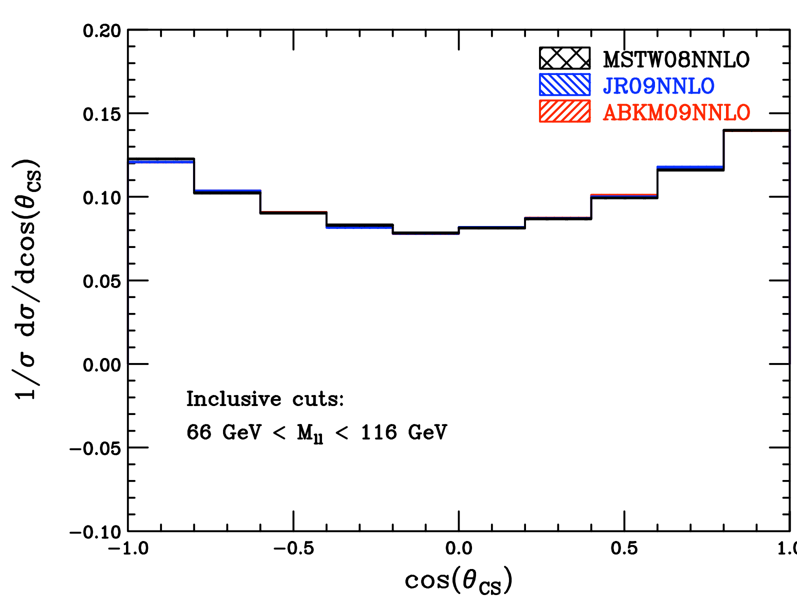
Fully Exclusive W and Z

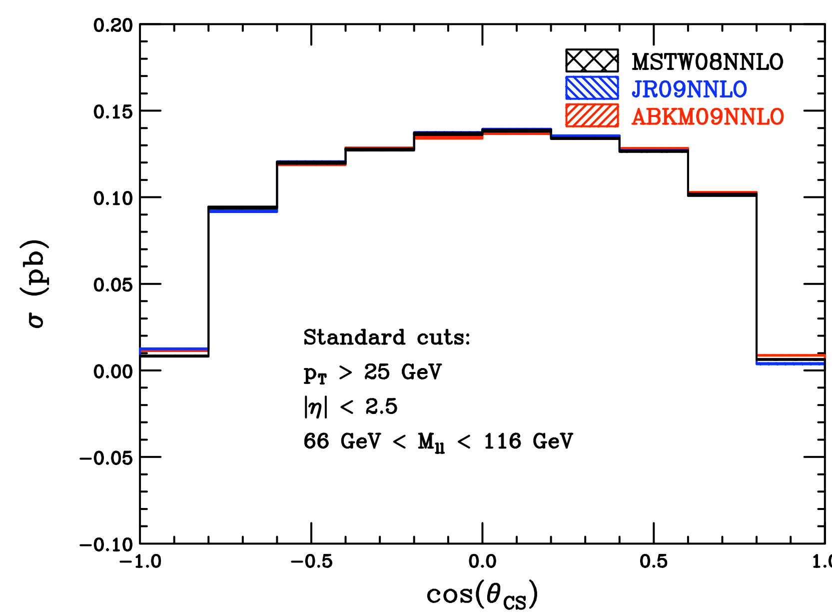
R. Gavin, Y. Li, FP, S. Quackenbush, Comput.Phys.Commun. (2011) in press

NU student ANL postdoc

- Original next-to-next-to-leading order (NNLO) QCD calculation and program: K. Melnikov, FP (2006)
- One of only two pp processes for which differential NNLO known
- But code inefficiency severely limited applications
- Complete re-write with major improvements
  - ☑ Now fills histograms of multiple, arbitrary variables during single run
  - ☑ Parallelization of integration routines to make use of CPU grids
  - ☑ PDF reweighting to obtain PDF errors for all observables in single code run
  - ☑ Optimized sector combination based on correlation study, improves integration efficiency dramatically: significant use of ANL computing resources!

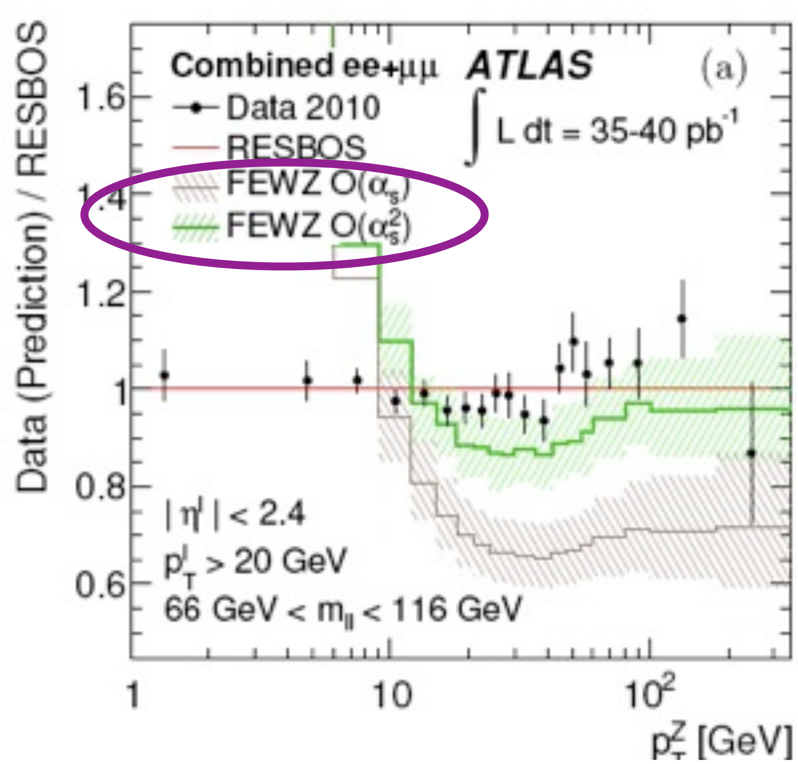


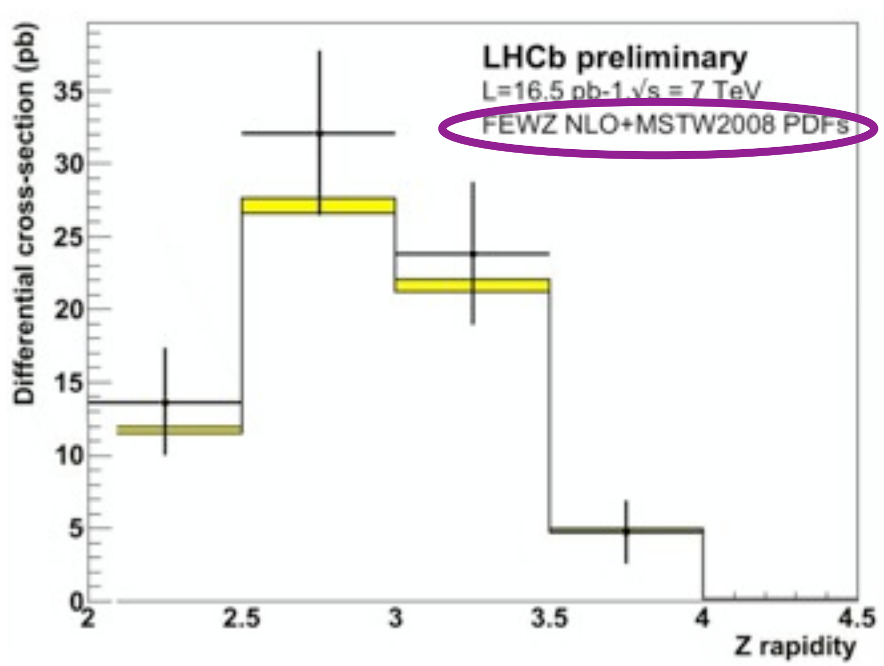




all 3 plots from single run

Diversity of EW physics

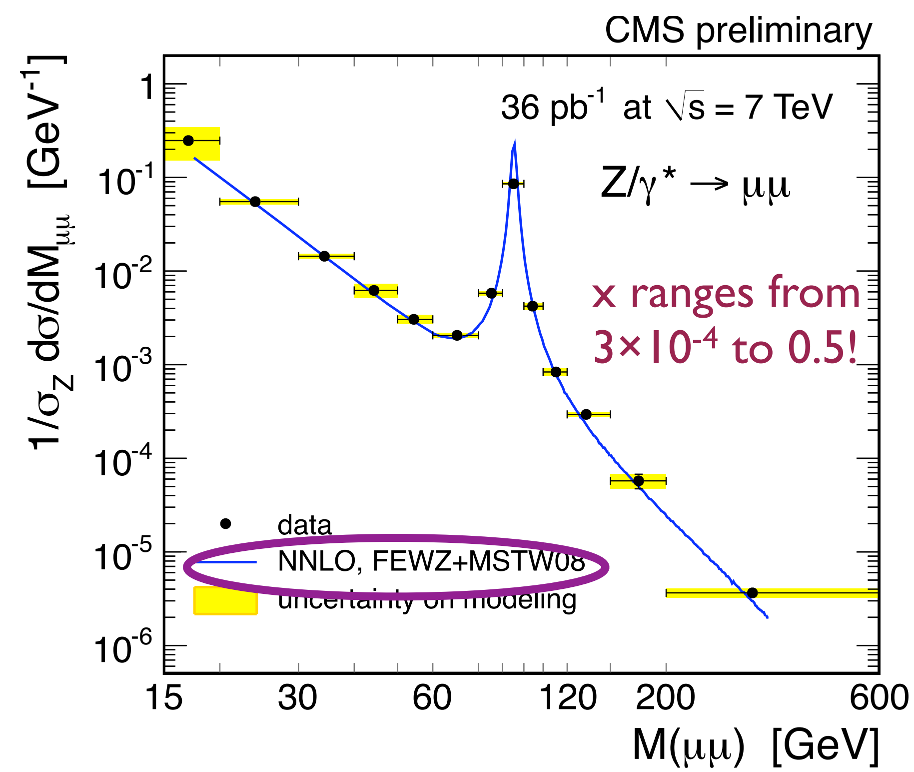


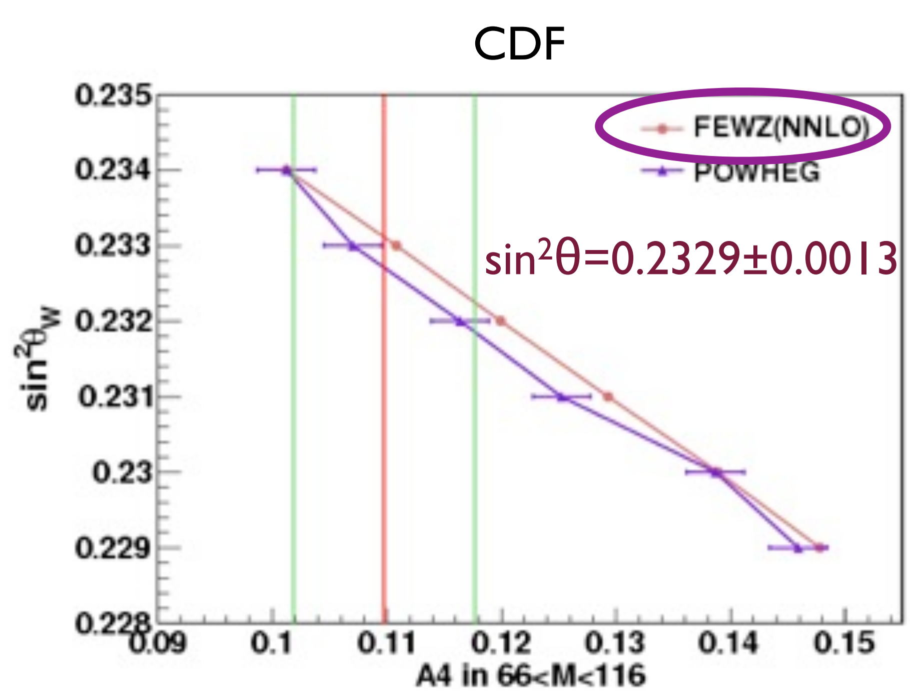


☑ All LHC, Tevatron measurements now have one thing in common: **FEWZ**

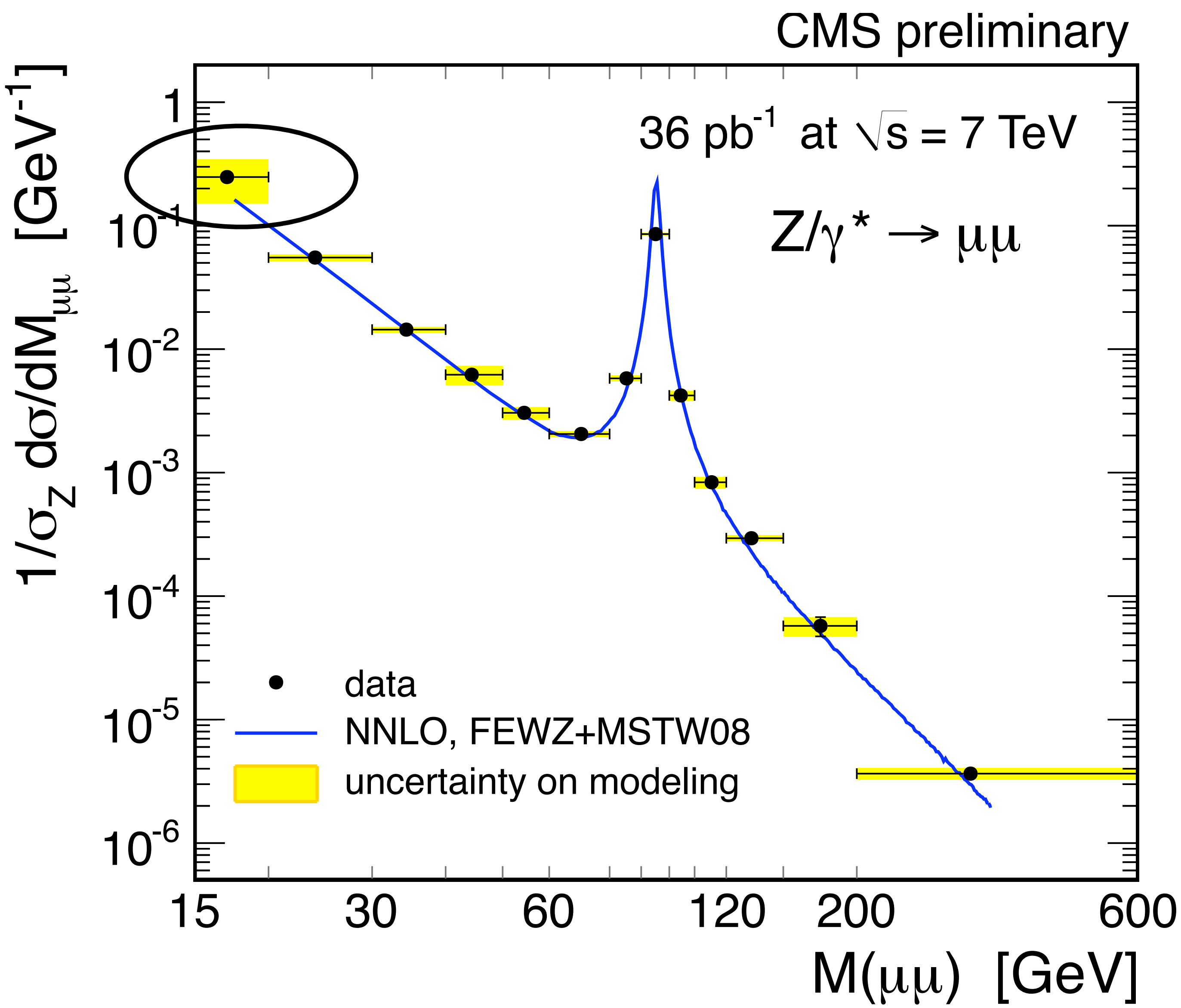
☑ These studies not possible with old FEWZ

☑ Constant interaction with experimentalists working on LHC studies





Fully Exclusive W and Z



- Double muon trigger: p_{T1}>16 GeV, p_{T2}>7 GeV
- For M=[15,20] GeV: NLO→LO, NNLO→NLO, need a hard jet to generate this configuration
- α_S(15 GeV)≈0.17, K-factor≈1.9 when going from 'N'LO→'N'NLO
- Corrections to POWHEG approaching 2

☑ Important to have tools incorporating all our knowledge to catch effects like this

Future FEWZ plans: incorporations of NLO EW corrections, avoid unfolding for FSR effects

Ed Berger: QCD/SM Phenomenology

Double Parton Scattering (DPS) at the LHC:

two "independent" hard scatters for each pp collision

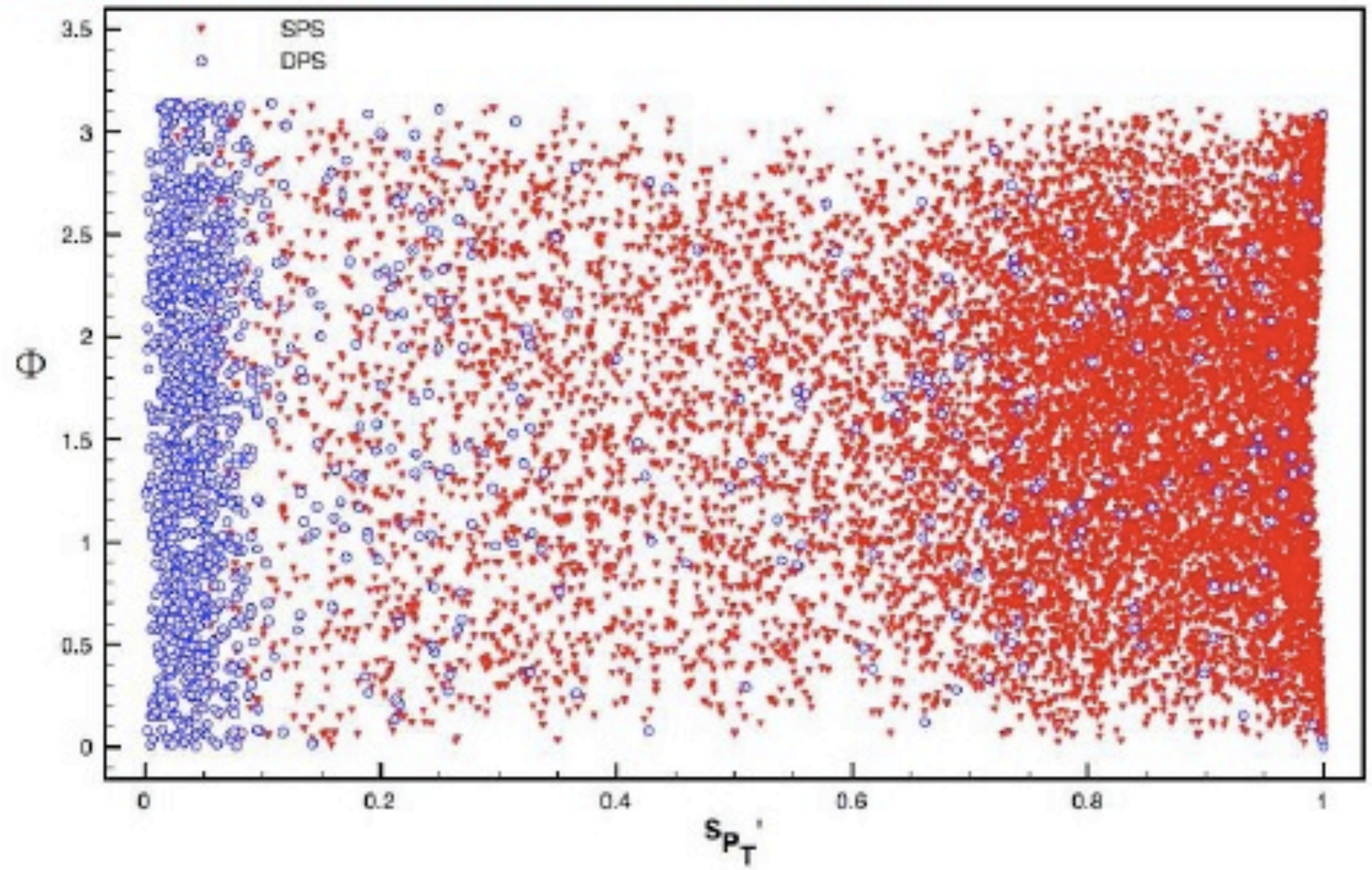
- $pp \to b\bar{b}jjX$, with Chris Jackson and Gabe Shaughnessy, Phys Rev D 81, 014014 (2010)

  Former ANL postdoc, now Texas-Arlington faculty
- $pp \to Wb\bar{b}X$, with Seth Quackenbush and Chris, Gabe, arXiv:1107.3150

  e.g. one scatter produces the W and the other the $b\bar{b}$

- Aim: identify signature variables and regions in phase space that distinguish DPS events from the usual single parton scattering SPS events
- Establish a methodology to measure the size of DPS
- Once established in a well defined process, then DPS contributions in other final states can be considered; possibly important for background estimates in new physics searches

Two-dimensional distribution



$$S'_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|p_T(b_1,b_2)|}{|p_T(b_1)|+|p_T(b_2)|}\right)^2 + \left(\frac{|p_T(j_1,j_2)|}{|p_T(j_1)|+|p_T(j_2)|}\right)^2}$$

- Φ: angle between the two planes defined by $b\bar{b}$ and jj systems

Clear separation of DPS from SPS in the 2-D Φ and S'_{p_T} plane

ATLAS and CMS are working on this analysis

2. Other Recent QCD Publications

- Helicity amplitudes for $uu \to tt \to bW^+(\to l^+\nu)bW^+(\to l^+\nu)$ to retain full spin correlations in same sign tt pair production and decay, plus implementation in Monte Carlo codes. Used in our studies of new physics processes in same sign top quark pair production, ELB with Qing-Hong Cao, arXiv:1005.2622, arXiv:1009.5379, and arXiv:1101.5625
- Parton distribution functions, ELB with Pavel Nadolsky, Phys. Rev. D **82**, 114023 (2010) (arXiv:1010.4315 (hep-ph))
- SM sources of isolated leptons, ELB with Zack Sullivan, Phys. Rev. D **82**, 014001 (2010) (arXiv:1003.4997 (hep-ph))
- NLO cross sections for 4th generation quarks and leptons, ELB with Qing-Hong Cao, P R D **81**, 035006 (2010) (arXiv:0909.3555 (hep-ph))
- Longitudinal parity-violating asymmetry in hadronic decays of weak bosons in polarized pp collisions, ELB with Pavel Nadolsky, Phys. Rev. D **78**, 114010 2008 (arXiv:0810.0020 (hep-ph))

3. *Future Research Plans – Berger*

- LHC results will set the course, however they turn out
- Work with ANL postdocs on interpretations of LHC and Tevatron phenomena; propose new measurements; extract maximum information from data
- Continue productive interactions with Argonne ATLAS Analysis Center

- perturbative QCD for production processes; new physics signals and SM look-alikes
- Higgs boson and BSM phenomenology
- top quark physics; polarization tests
- extra neutral and charged gauge bosons, W' and Z'

Structure of pQCD at Higher Orders

Infrared structure at NNLO

R. Boughezal et al., JHEP 1102 (2011) 098; PoS DIS2010 (2010) 101

- Can't yet provide 2→2 scattering beyond next-to-leading order!
- NNLO phenomenologically needed for jet production, V+jet, ttbar, ...
- Only two possible techniques known; ANL group advancing knowledge in both directions

Problem:

- differential cross sections require jet functions. Jet functions are functions that allow for arbitrary cuts on the phase space
- the presence of the jet function doesn't make it possible to integrate analytically

Solution: extract the IR singularities of the real radiation using IR subtraction terms.

$$
\begin{aligned}
d\hat{\sigma}_{NNLO} = & \int_{d\Phi_{m+2}} \left(d\hat{\sigma}^{R}_{NNLO} - d\hat{\sigma}^{S}_{NNLO}\right) + \int_{d\Phi_{m+2}} d\hat{\sigma}^{S}_{NNLO} \\
& + \int_{d\Phi_{m+1}} \left(d\hat{\sigma}^{V,1}_{NNLO} - d\hat{\sigma}^{VS,1}_{NNLO}\right) + \int_{d\Phi_{m+1}} d\hat{\sigma}^{VS,1}_{NNLO} + \int_{d\Phi_{m+1}} d\hat{\sigma}^{MF,1}_{NNLO} \\
& + \int_{d\Phi_{m}} d\hat{\sigma}^{V,2}_{NNLO} + \int_{d\Phi_{m}} d\hat{\sigma}^{MF,2}_{NNLO}.
\end{aligned}
$$

Antenna functions: derived from physical matrix elements normalized to two-parton matrix elements

Previously worked out for e^+e^- and DIS processes, but difficult and intricate to extend to hadron-hadron collisions (e.g., 4 master integrals for e^+e^- becomes 32 for LHC)

Infrared structure at NNLO

R. Boughezal et al., JHEP 1102 (2011) 098; PoS DIS2010 (2010) 101

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& + \int_{d\Phi_{...}} d\hat{\sigma}^{V,2}_{NNLO} + \int_{d\Phi_{...}} d\hat{\sigma}^{MF,2}_{NNLO}.
\end{aligned}
$$

Antenna functions: derived from physical matrix elements normalized to matrix elements

☑ Extension worked out by Boughezal et al.; subset of integrated subtraction terms provided.

Remaining are: 

$$
\begin{aligned}
\mathcal{B}_{12} = & -\frac{1}{\varepsilon^3}\left\{\frac{\delta(1-x_1)\,\delta(1-x_2)}{12}\right\} \\
& +\frac{1}{\varepsilon^2}\left\{\delta(1-x_1)\left(-\frac{1+x_2}{12}+\frac{1}{6}\mathcal{D}_0(x_2)-\frac{5}{36}\delta(1-x_2)\right)\right. \\
& \left.+\left(\frac{1}{6}\mathcal{D}_0(x_1)-\frac{1+x_1}{12}\right)\delta(1-x_2)\right\}+\mathcal{O}\left(\frac{1}{\varepsilon}\right). \\
\mathcal{B}_{13} = & \frac{1}{\varepsilon^2}\delta(1-x_1)\left\{\frac{(1-x_2)(4x_2^2+7x_2+4)}{24x_2}+\frac{1+x_2}{4}H(0,x_2)\right\} \\
& +\mathcal{O}\left(\frac{1}{\varepsilon}\right).
\end{aligned}
$$

Sector decomposition

R. Boughezal, FP

- Numerical technique, originally devloped and applied to W, Z, Higgs production Anastasiou, Melnikov, FP 2003-2005; Melnikov, FP 2006
- These are the only differential NNLO results available for hadron-collider studies

Cast NNLO singularities in the form:

$$I = \int_0^1 \mathrm{d}x\,\mathrm{d}y\, x^{-1-\epsilon} y^{-1-\epsilon} (x+y)^{-\epsilon}$$

$$\Downarrow$$

$$I_1 = \int_0^1 \mathrm{d}x\,\mathrm{d}y\, x^{-1-3\epsilon} y^{-1-\epsilon} (1+y)^{-\epsilon}, \quad I_2 = \int_0^1 \mathrm{d}x\,\mathrm{d}y\, y^{-1-3\epsilon} x^{-1-\epsilon} (1+x)^{-\epsilon}$$

Expand in plus distributions

Simple idea, but was very process-dependent; the "x,y" in this example took on numerous completely different forms in every example

- Recent work has suggested how to remove this limitation Czakon, 2010
- Limited (~10) decompositions to understand for any process, upon suitable partitioning of phase-space
- Idea not yet tested; we are actively investigating what is entailed in applying this idea to the computation of LHC cross sections

Dimensional reconstruction at NNLO

R. Boughezal, K. Melnikov, FP arXiv:1106.5520

- Can we use 4-dimensional helicity (FDH) rather than conventional dim. reg. (CDR) at NNLO?
- FDH: spin d.o.f. in d_s=4; a greatly reduces needed real radiation MEs
- Also just interesting to know, is this a consistent regularization scheme?

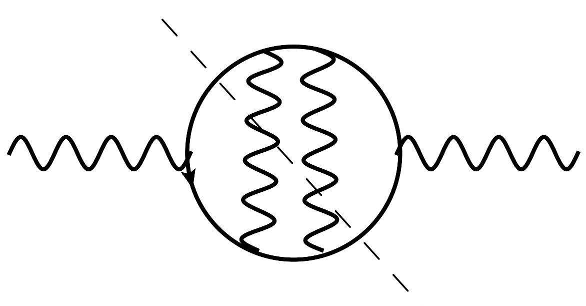
FDH inconsistent at NNLO!

W. Kilgore, 2011

$$\mathrm{Im}\left[\Pi(q^2)\right]^{\mathrm{CDR}} = \frac{1}{12\pi}\left[1+\frac{3}{4}\left(\frac{\alpha}{\pi}\right) - \frac{3}{32}\left(\frac{\alpha}{\pi}\right)^2\right],$$

$$\mathrm{Im}\left[\Pi(q^2)\right]^{\mathrm{FDH}} = \frac{1}{12\pi}\left[1+\frac{3}{4}\left(\frac{\alpha}{\pi}\right) - \frac{15}{32}\left(\frac{\alpha}{\pi}\right)^2\right].$$

Computation of finite quantity differs in two schemes!



- ☑ We found how to fix this using ideas from extra-dimensional theories

$$\mathrm{Im}\left[\Pi(q^2)\right]^{\mathrm{CDR}} = \mathrm{Im}\left[\Pi(q^2)\right]^{\mathrm{FDH}} - \frac{c_1}{6\pi}\left(\frac{\alpha}{\pi}\right)^2$$

- ☑ Fix c_1 by computing in 5D, 6D; only need coupling constant renormalization in 5D, 6D, can avoid the full NNLO CDR calculation!

$$c_1 = \frac{3\pi}{4\alpha}\epsilon\left(\delta Z_5 - \frac{1}{2}\delta Z_6\right)$$

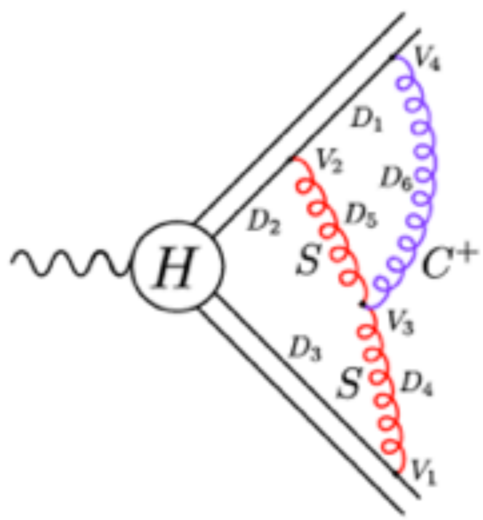
- ☑ Demonstrated with several examples. This idea will be central in future higher-order calculations.

Factorization and Resummation in QCD

Closing a Loop-Hole in Proofs of Factorization Theorems

G.T. Bodwin (ANL), J. Lee (Korea U.), X. Garcia i Tormo (ANL, U. of Alberta)
Phys. Rev. D **81**, 114005 (2010)
Former ANL postdoc

- In QCD, low-energy collinear gluons can couple to soft gluons at leading order in the large momentum transfer Q:



$$
\begin{aligned}
\text{volume of integration} &\sim Q^8\epsilon_S^4(\epsilon^+)^4(\eta^+)^4\\
V_1\cdot V_2 &\sim Q^2\\
V_3\cdot V_4 &\sim \epsilon_S Q^2\\
D_1 &\sim 1/[Q^2\epsilon^+(\eta^+)^2]\\
D_2 &\sim 1/(Q^2\epsilon_S)\\
D_3 &\sim 1/(Q^2\epsilon_S)\\
D_4 &\sim 1/(Q^2\epsilon_S^2)\\
D_5 &\sim 1/[Q^2(\epsilon_S^2+\epsilon_S\epsilon^+)]\\
D_6 &\sim 1/[Q^2(\epsilon^+)^2(\eta^+)^2]
\end{aligned}
$$

$$k_S \sim Q\varepsilon_S(1,1,\mathbf{1}_\perp)$$

$$k_{C^+} \sim Q\varepsilon^+[1,(\eta^+)^2,\boldsymbol{\eta}_\perp^+]$$

- This situation is not treated properly in traditional graphical proofs of factorization or in proofs in soft-collinear effective theory (SCET).

- Bodwin and collaborators pointed out this fact and devised new all-orders methods to deal with it in factorization proofs.

- They demonstrated the new methods by proving to all orders in α_s that the traditional factorization formula holds for $e^+e^- \to$ light meson $+$ light meson.

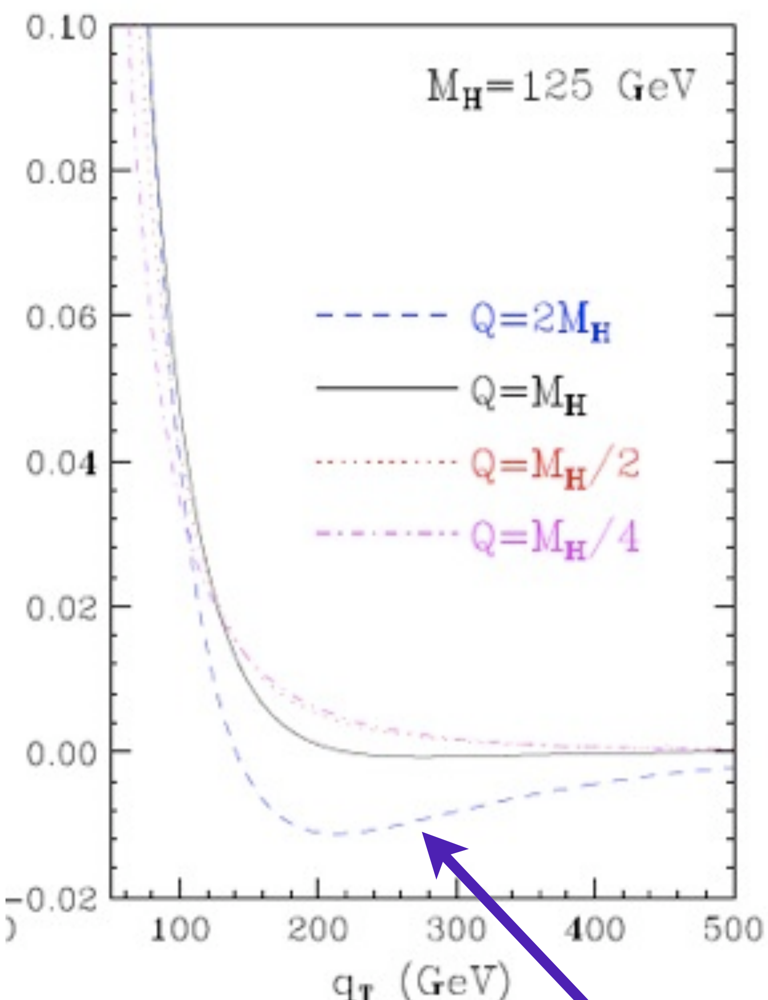
- May be important in resumming logarithms and in removing singularities from calculations in QCD at NNLO and higher.

Low p_T in the EFT approach

Y Li, S. Mantry, FP PRD 81:093007 (2010); PRD 83:053007 (2011); PRD 84:014030 (2011); arXiv:1105.5171

NU student NU/ANL LHC-TI fellow

- Many reasons to understand low p_T production: M_W, Higgs in WW mode
- Standard approach uses b-space; serious issues arise when converting to momentum-space

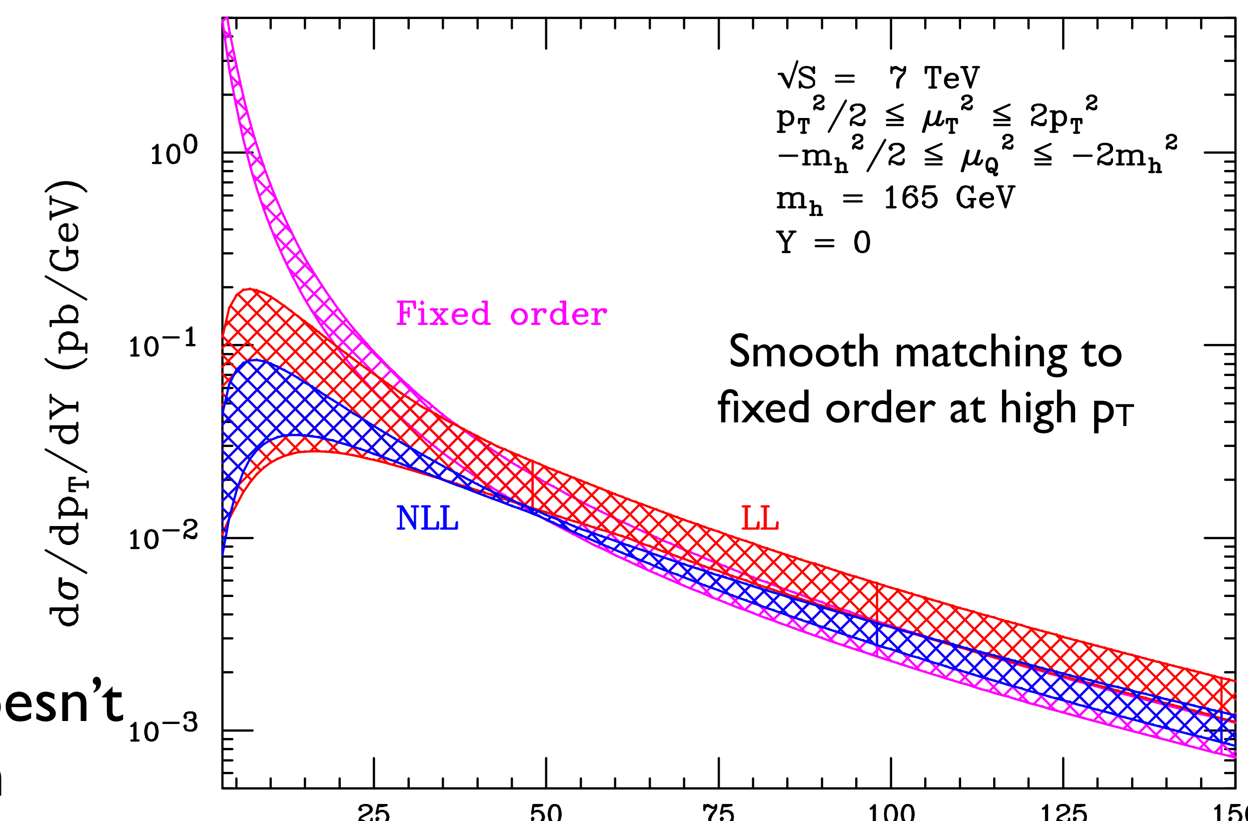


Bozzi, Catani, de Florian, Grazzini 2005

Negative cross section! Resummed exponent doesn't turn off in high p_T region

- Should not use to reweight PYTHIA p_T spectrum above intermediate momenta (M. Grazzini), but done anyway

☑ We've developed a SCET approach that resolves this issue
☑ Also addresses several conceptual issues affecting other approaches (rapidity divergences, operator definitions)
☑ Agrees with Tevatron data!



Extending to NNLL, comparison with LHC data:

Many-loop QFT and Phenomenology

g-2 and hadronic light-by-light

R. Boughezal, K. Melnikov arXiv:1104.4510

$$a_\mu^{\rm exp} = 11\ 659\ 2080(63) \times 10^{-11}$$

$$a_\mu^{\rm th} = 11\ 659\ 1790(65) \times 10^{-11}$$

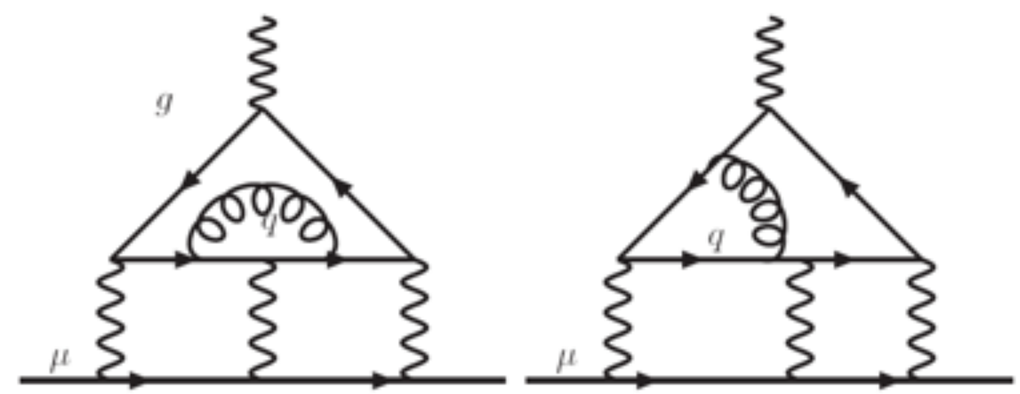
Will continue running at FNAL in a few years!

– a_μ obtained by combining QED, Electroweak and hadronic contributions

under very good control   VP + hLBL

- Recent work: hLBL estimates are off by a factor of 2 or more due to QCD effects on the quark-photon vertex, Goecke et al., 2010. Reduces discrepancy.

- Need 4-loop QCD to test
- Use the constituent quark model as a model of QCD non-perturbative effects. Fit the masses using hadronic vacuum polarization, then use in hLBL Pivovarov 2003; Erler, Sanchez 2006
- Are there large QCD effects to hLBL that don't appear in hVP? If not, tough to swallow the factor of 2 claim.



$$a_\mu^{\rm hlbl} = R^{\rm NLO}\, a_\mu^{\rm hvp} \qquad R^{\rm NLO} = f\left(\frac{\alpha_s}{\pi}\right)\frac{\alpha}{\pi}\left(\frac{3}{2}\zeta_3 - \frac{19}{16}\right)\frac{45\langle Q_q^4\rangle}{\langle Q_q^2\rangle}$$

$$f(0) = 1 \qquad f(1) = 0.8 \quad f(\infty) = 0.76$$

Very insensitive to QCD effects! Strengthens 3 sigma discrepancy between experiment and SM.

Quarkonium as a QCD Laboratory

The Importance of Heavy-Quarkonium Physics

- A useful theoretical laboratory for understanding the interplay between perturbative and nonperturbative QCD.
  - The heavy-quark expansion gives better theoretical control over nonperturbative effects.
  - Potential models are valid.
  - The Fock-state expansion is expansion is well controlled.
- Insights gained in studying heavy quarkonium will likely be important in other areas.
  - Surprising enhancements of NLO (NNLO) cross sections by an order of magnitude compared to LO (NLO) cross sections.
  - All-orders resummation of the velocity expansion may have implications for resummation of higher-twist effects in light-hadron processes.
- There is a great deal of activity in heavy-quarkonium in collider experiments.
  - CDF, D0, Belle, BESII, ALICE, ATLAS, CMS, LHCb, PHENIX, STAR all have active programs in heavy-quarkonium physics.
  - Already 47 papers on quarkonium physics have been written by the LHC experiments. Many more LHC results to come.
- We should take advantage of the wealth of experimental information to learn more about QCD.

New Method for Computing NLO Quarkonium Rates to All Orders in v

G.T. Bodwin (ANL), H.S. Chung (Korea U.), J. Lee (Korea U.), C. Yu (Korea U.)

Phys. Rev. D **79**, 014007 (2009)

- Computation of quarkonium decay and production rates requires matching of amplitudes between full QCD and Nonrelativistic QCD (NRQCD).
- At one-loop level, the matching calculation at all orders in the heavy-quark velocity v is daunting.
  - Requires operators and coefficients of all orders in v.
  - Requires one-loop renormalizations of operators by interactions of all orders in v.
- New Method: Compute the NRQCD part of the matching by making a nonrelativistic expansion of the full QCD expression for the integrand.
  - Equivalent to calculating in NRQCD, but the bookkeeping is much simpler.
  - Computes the potential and usoft contributions of the method of regions in one step. Because of the correspondence to NRQCD, there are no double-counting issues.
  - In dim. reg., the expressions are very simple and can be resummed to all orders in v.
- Application to the heavy-quark electromagnetic current
  - Important for decay and production of quarkonium through a virtual photon (e^+e^- colliders).
  - The all-orders resummation agrees with all of the previously known results at orders α_s^0, α_s^1, v^0, and v^2.

Gluon Fragmentation to a color-singlet $Q\bar{Q}$ pair in order v^4

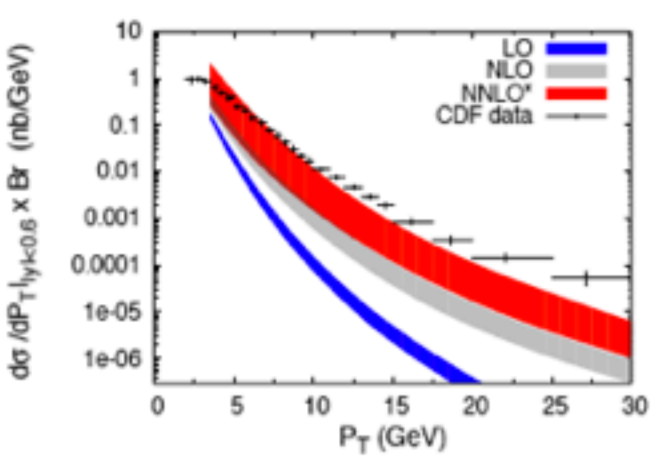
G.T. Bodwin (ANL) and J. Lee (Korea U.)

- Gluon fragmentation to a color-octet $Q\bar{Q}$ pair is thought to be the dominant J/ψ production mechanism at large p_T.
- Gluon fragmentation to a color-singlet $Q\bar{Q}$ pair at order v^4 is connected to gluon fragmentation to a color-octet $Q\bar{Q}$ pair through a logarithm of the factorization scale.
  - v is the Q or $\bar{Q}$ velocity in the $Q\bar{Q}$ CM frame.
- Suggests that gluon fragmentation to a color-singlet $Q\bar{Q}$ pair may be important at order v^4. Only the sum of the octet and singlet contributions is independent of the factorization scale.
- The calculation is difficult technically because it involves single and double infrared divergences and mixing of the color-singlet $^3S_1$ operator with color-octet $^3S_1$ and ^3P_J operators.
- This is the first NRQCD calculation involving two-loop operator renormalizations.
- Work on this lengthy calculation is nearing completion.

Heavy Quarkonium: Progress, Puzzles and Opportunities

Nora Brambilla (TU München), G.T. Bodwin (ANL), *et al.*
Eur. Phys. J. C71, 1534 (2011)

- Members of the Quarkonium Working Group (QWG) have prepared a comprehensive (181 page) document that describes recent progress in quarkonium physics and the outstanding current issues in experiment and theory.
- The document also summarizes new opportunities in quarkonium physics at present and future facilities.
- Topics covered are spectroscopy, decay, production, production in media, and the experimental outlook.
- Bodwin was a coordinator and principal author of the section on production.
- Example:



The gap between higher-order color-singlet contributions and the CDF data for the $\psi(2s)$ suggests the presence of a color-octet contribution that could be detected at the LHC.

Final comments

- Intense activity at ANL into all areas of pQCD: from collider energies to g-2, foundational issues to simulation codes and numerics
- Expect even more activity beginning in the fall joined by 3 postdocs with primary interest in QCD: S. Mantry (LHC-TI fellow with NU), M. Schulze (ANL Director's Fellow), X. Liu (joint ANL/NU)$\Rightarrow$2 of these with external funds
- See submitted write-up for a global listing of group's QCD work

Factorization Theorems for Exclusive Quarkonium Production

G.T. Bodwin (ANL), J. Lee (Korea U.), X. Garcia i Tormo (ANL, U. of Alberta)
Phys. Rev. Lett. **101**, 102002 (2008)
Phys. Rev. D **81**, 114014 (2010)

- Bodwin and collaborators established factorization theorems for
  - $e^+e^- \rightarrow$ charmonium $+$ charmonium,
  - $B \rightarrow$ light meson $+$ charmonium.
- Hold to all orders in α_s up to corrections of order
  - $(m_c v^2)^2/s$ for e^+e^- annihilation to two S-wave charmonia,
  - $m_c v^2/m_b$ for B-meson decays to an S-wave charmonium.
- These are the first factorization theorems to be proven for quarkonium production.
- The extensive paper in Phys. Rev. D contains details of these proofs and one-loop examples.
- The proofs hold only for non-helicity-flip processes.
  Work on extending them to helicity-flip processes is in progress.

Two important distinguishing variables

- Φ: angle between the planes defined by $b\bar{b}$ and jj systems.
  Uncorrelated scatters: the DPS Φ distribution is flat. In SPS, $p + p \to b\bar{b}jjX$, many QCD diagrams contribute; spin and kinematic correlations are expected between the planes
- S'_{p_T} exploits back-to-back nature of the $2 \to 2$ subprocesses ($p_T(1,2)$: vector sum of the p_T's of 1 and 2)

$$S'_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|p_T(b_1,b_2)|}{|p_T(b_1)|+|p_T(b_2)|}\right)^2 + \left(\frac{|p_T(j_1,j_2)|}{|p_T(j_1)|+|p_T(j_2)|}\right)^2}$$

DPS events produce a clear peak near $S'_{p_T} = 0$, well separated from the total. SPS events are away from back-to-back (gluon splitting)